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Leakage Potential of Underground Storage Tanks

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The U.S. Army owns more than 15,000 underground storage tanks (USTs), many of which are old and may be leaking. In order to manage the large amounts of information on Army USTs, USACERL developed a microcomputer-based database system that was first distributed to Major Army Commands (MACOMs) in 1987. Data in the system, currently being updated, can be combined with soil information to indicate the leakage potential of USTs under Army jurisdiction. This report details development of a Leak Potential Index (LPI) and profiles the Army's UST database in terms of construction material, capacity, age, content, and LPI.

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FOREWORD

This research was conducted for the U.S. Army Engineering and Housing Support Center (USAEHSC), under Project 41A62720A896, "Environmental Quality Technology"; Work Unit NN-TXO, "Leaking Underground Storage Tanks." The technical monitor is Tom Wash, CEHSC-FU-S.

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CONTENTS

	SF 298	1
	FOREWORD	2
	LIST OF FIGURES AND TABLES	4
1	INTRODUCTION	5
	Background	
	Objective	
	Approach	
	Mode of Technology Transfer	
2	OVERVIEW—UNDERGROUND STORAGE TANKS AND THEIR REGULATION	7
	Types of Underground Storage Tanks	
	Leaking Underground Storage Tanks	
	Regulations	
3	LEAK POTENTIAL INDEX FOR UNDERGROUND STORAGE TANKS	13
	Background	
	Factors Influencing Underground Storage Tank Corrosion	
	Development of Leak Potential Index Equation	
	Analysis Based on UST Leak Data	
	Analysis Based on Corrosion Mechanism	
	Leak Potential Index Equation	
4	CHARACTERISTIC PROFILE OF ARMY'S UNDERGROUND STORAGE TANKS	23
	UST Database	
	Construction Material	
	Capacity	
	Age	
	Tank Contents	
	Leak Potential Index (LPI)	
5	CONCLUSIONS AND RECOMMENDATIONS	31
	Conclusions	
	Recommendations	
	METRIC CONVERSION TABLE	32
	REFERENCES	33
	ABBREVIATIONS	35
	DISTRIBUTION	

FIGURES

Number		Page
1	Gasoline Movement From a Leaking UST	9
2	A Fiberglass-Reinforced Plastic (FRP) UST During Installation	9
3	Corrosion Around an Opening on the Surface of a Steel UST	10
4	Leaking Tank Chart Indicating the Relationship Between Soil Aggressiveness Values and Age	17
5	Nonleaking Tank Chart Indicating the Relationship Between Soil Aggressiveness Values and Age	18
6	Distribution of the 15,284 USTs Among MACOMs	24
7	Distribution of USTs According to Construction Material Among MACOMs	25
8	Distribution of USTs According to Capacity (in Gallons) Among MACOMs	26
9	Distribution of USTs According to Age (in Years) Among MACOMs	29
10	Distribution of USTs According to Content by MACOM	29
11	Distribution of USTs By Capacity (In Gallons) for All USTs Containing Heating Oil	30
12	Distribution of USTs According to LPI Among MACOMs	30

TABLES

1	Computation of Soil Aggressiveness Values	16
2	UST Shell Thickness as a Function of Capacity	22
3	Soil Aeration Constants	22

LEAKAGE POTENTIAL OF UNDERGROUND STORAGE TANKS

1 INTRODUCTION

Background

Underground storage tanks (USTs) are used to store motor fuel and other hazardous substances throughout the United States. The U.S. Environmental Protection Agency (USEPA) estimates there are more than 1.4 million tanks in the country, of which the Army owns some 15,000. Almost 35 percent of them may be leaking.¹

The Resource Conservation and Recovery Act (RCRA)² of 1976 required owners of tanks with capacities greater than 1100 gallons to notify the USEPA by May 1986. This information was used to locate and evaluate underground tanks containing petroleum or other hazardous substances. In September 1988, the USEPA published final rules for UST management that cover the technical requirements pertaining to design, installation, testing, and monitoring, as well as clean-up following leaks.³

In 1987 The U.S. Army Construction Engineering Research Laboratory (USACERL) developed a microcomputer based system that Major Army Commands (MACOMS) could use to store, organize, and manipulate data about USTs on their installations.⁴ This system has recently been upgraded to make it easier to use, and its database, derived from USEPA information about construction material, capacity, age, and contents of USTs, is being expanded and updated. If properly manipulated, this data can also provide Army managers with information about the leakage potential of underground storage tanks.

Objective

The objective of this report is to detail development of the Leak Potential Index (LPI) and present results of an LPI analysis of the Army's UST database.

Approach

The information compiled in this report was obtained by analyzing USEPA data to profile the construction material, capacity, age, and contents of USTs on Army installations. Chapter 2 presents an

¹ Westat, Inc., Midwest Research Institute, Battelle Columbus Division, and Washington Consulting Group, *Underground Motor Fuel Storage Tanks. A National Survey*, Project Report (U.S. Environmental Protection Agency [USEPA], 1986).

² Public Law 94-480, *Resource Conservation and Recovery Act* (1976).

³ 40 Code of Federal Regulations (CFR) Parts 280-281, *Underground Storage Tanks. Technical Requirements and State Program Approval*, Final Rule, (23 September 1988), pp 37081-37247.

⁴ B.A. Donahue, Theresa J. Hootor, and Kemal Piskin, *Managing Underground Storage Tank Data Using dBase III Plus*, Technical Report (TR) N 87/21/ADA182452 (U.S. Army Construction Engineering Research Laboratory [USACERL], June 1987); S. Dharmavaram, K. Piskin, T.J. Hootor, and B.A. Donahue, "A Profile and Management of the U.S. Army's Underground Storage Tanks," *Environmental Management*, Vol 13, No. 3 (1989) pp 333-333.

overview of USTs and the latest rules and regulations. Chapter 3 discusses the methodology used to determine the LPI, and Chapter 4 presents the findings.

Mode of Technology Transfer

The updated UST database system is being distributed to all MACOMs. The findings of this report should be used by MACOMS and installations to identify and correct problems.

2 OVERVIEW—UNDERGROUND STORAGE TANKS AND THEIR REGULATION

Types of Underground Storage Tanks

An underground storage tank (UST) is defined as a tank, including its piping, that has at least 10 percent of its volume underground.⁵ Such tanks are primarily used to store liquid petroleum and hazardous chemicals.

The types of USTs in use can be classified as: bare steel tanks not protected from corrosion; steel USTs protected with a noncorrodible coating, such as coal-tar epoxy, urethane, or fiberglass-reinforced plastic (FRP); steel USTs with protection from electrochemical reactions; steel USTs with a noncorrodible coating and electrochemical protection; USTs made totally of noncorrodible materials, usually FRP; and noncorrodible or protected USTs that also use secondary containment systems (mainly double-walled tanks, pit lining systems, and vaults). There are also some concrete USTs. FRP, unlike steel, is a recent UST material, having been used only since about the mid-1960s.

Of the approximately 1.4 million USTs in use at over 700,000 facilities in the United States, an estimated 75 percent are unprotected bare steel tanks. Most of the other 25 percent are FRP, protected steel, and steel-FRP composite tanks.⁶ Some of the USTs may be compartmentalized to store more than one substance. They usually have top center openings (to make internal inspection and cleaning easier) and ancillary openings (such as fill pipe suction and vent lines). Their capacity, depending on use, may range from a few gallons to several thousand gallons. Some of the Department of Defense's largest USTs can hold several million gallons.

USTs are commonly built as horizontal cylinders, but some are vertical. Most of them are completely constructed in a factory, but some of the larger ones are built at the installation site.

Leaking Underground Storage Tanks

Results of a survey of 12,444 USTs in 50 states conducted for the USEPA by Versar, Inc.,⁷ indicate a steady increase in leaks—or "release incidents"—since 1970. Approximately 83 percent (about 10,300 incidents) of the leaks documented at the state level involved tanks covered by the recent USEPA regulations. These leaks contaminated 749 private water wells and 40 municipal wells. They also involved 100 cases of human illness, 155 cases of fire and explosion (resulting in two deaths), 202 cases of damage to plants or wildlife, and 908 reports of combustible fumes in confined areas.

When compared to abandoned facilities, operating facilities were responsible for about 95 percent of the leaks. The distribution of release incidents shows that about 65 percent of the documented leaks involved retail gasoline service stations, including convenience stores and multipurpose retailers. Other commercial establishments accounted for 11 percent of the releases while manufacturing and municipal

⁵ Public Law 98-616, *Hazardous and Solid Waste Amendments, Title VI. Underground Storage Tanks, Subtitle I - Regulation of Underground Storage Tanks* (November 1984).

⁶ 40 CFR Parts 280 -281 (23 September 1988) pp 37082-37247.

⁷ Versar, Inc., *Analysis of the National Data Base of UST Release Incidents*, EPA/600/M-86/020 (USEPA, Washington, D.C., July 1986), pp 1/1-9/18.

facilities accounted for 5 percent and 4 percent, respectively. Figure 1 illustrates the path of gasoline movement from a leaking UST to a public water supply.

Substances that have leaked from USTs include gasoline (over 70 percent), heating oil (about 15 percent), diesel fuel (about 6 percent), and recycled oil, chemicals, and others (about 9 percent).

The same USEPA survey⁸ also reports the locations and causes of the releases. More than 90 percent of the UST release reports identified the sources. About 43 percent identified the tank as the source of the leak and 18 percent identified the piping system. About 13 percent of the sources cited were either the piping, or a combination of the tank and piping. Tank overfills were cited in 17 percent of the cases. The rest of the leaks came from the pump or unknown sources.

Although most reports did not specify a cause of UST leaks, corrosion was the leading cause cited, followed by structural failure. Other reported causes included improper installation and operation, loose fittings, and incompatible materials. Piping failures usually occur before tank failure, because of poor installation. Since pipe walls are thinner than tank walls, they are more susceptible to corrosion-related leaks.

FRP tanks leak because of breakage caused by improper handling during transportation or installation (Figure 2). External corrosion, however, is the major cause of leaks from steel tanks.⁹ Figure 3 shows external corrosion developing around an opening of a steel tank.

Corrosion is an electrochemical process that involves oxidation and reduction reactions on a metallic surface. External corrosion of tanks is caused primarily by soil with high moisture content, low pH, low resistivity, and sulfide produced by bacterial activity. Other factors influencing external corrosion include high soil temperature, stray electrical currents, and the presence of dissimilar metal objects near (or connected to) the tank.

Internal tank corrosion is generally caused by chemical processes resulting from the interaction of water, oxygen, and bacteria. The chemical makeup of the stored substance, damage caused by the misuse of gauging sticks, and unnoticed damage that occurred during installation also cause and accelerate internal corrosion.

Regulations

The Hazardous and Solid Waste Amendments (HSWA)¹⁰ of 1984 require all UST owners to comply with all applicable Federal, State, interstate and local agency requirements. The regulations strongly support the RCRA¹¹ of 1976, the Federal law protecting human health and the environment from improper waste management. This program is administered by the USEPA through its Office of Underground Storage Tanks (OUST), which is part of the Office of Solid Waste and Emergency Response.

⁸Versar, Inc.

⁹John H. Fitzgerald, "Corrosion of Underground Storage Tanks," *Plant Engineering*, File Number 6502 (July 1983).

¹⁰Public Law 98-616, pp 1-73.

¹¹Public Law 94-480.

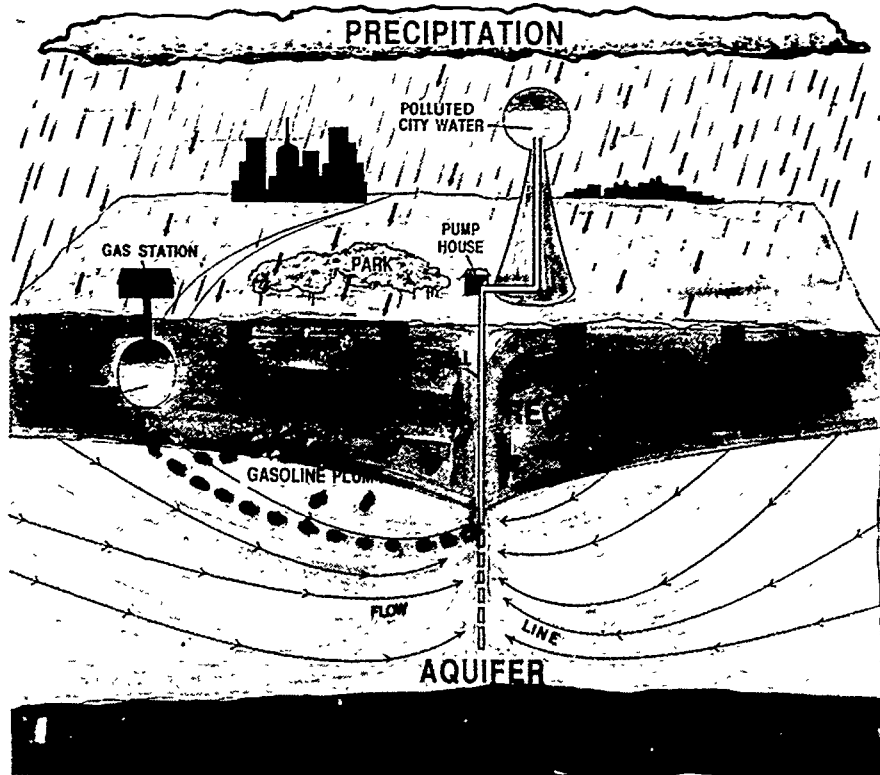


Figure 1. Gasoline movement from a leaking UST.



Figure 2. A fiberglass-reinforced plastic (FRP) UST during installation.

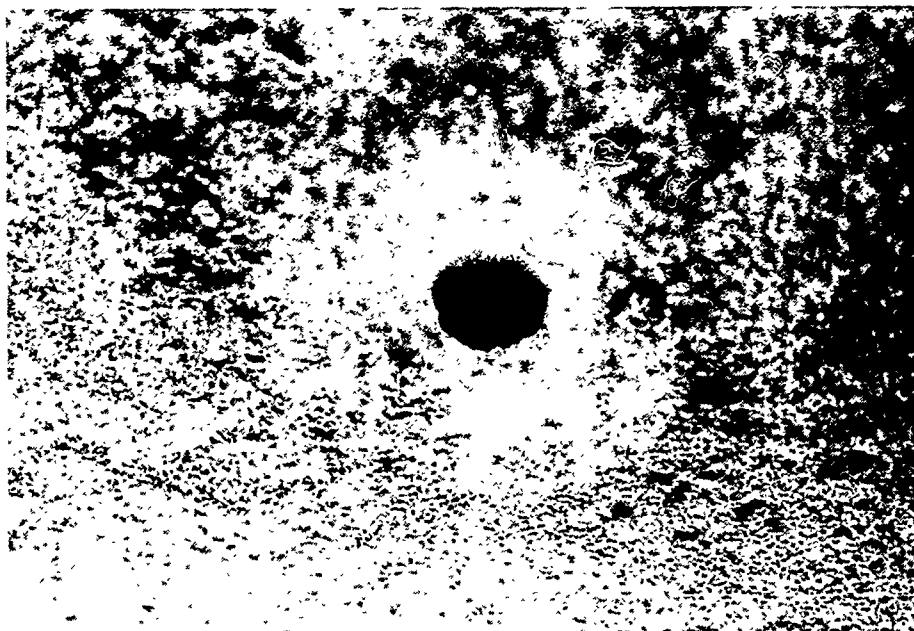


Figure 3. Corrosion around an opening on the surface of a steel UST.

USEPA's UST program, which includes banning underground installation of new tanks that do not meet certain minimum requirements, went into effect on 7 May 1985. USEPA also required UST owners to report existing tanks, including USTs taken out of operation after 1 January 1974 (but still in the ground). Tank owners were also required to notify the appropriate state authority by 8 May 1986.¹² After that date, owners of newly installed USTs had to notify the appropriate state or local agency within 30 days after bringing the tank into use. Notification forms (No. 7530-1) provide UST information such as location, material, age, size and uses.

Some of the above requirements no longer apply because their effective dates have passed, and some of them were revised by new regulations. The Final Rules covering the technical requirements and State program approval were published on 23 September 1988.¹³ Financial responsibility requirements for tank owners were published on 26 October 1988.¹⁴

The Final Rules are implemented under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, except for any substance regulated as a hazardous waste under Subtitle C of RCRA. One major portion of RCRA, as amended in Subtitle I, provides for the development and implementation of comprehensive regulation of USTs containing regulated substances.

¹² 40 CFR Part 280, *Notification Requirements for Owners of Underground Storage Tanks*, Final Rule (USEPA, November 1985), pp 46602-46619.

¹³ 40 CFR Parts 280-281, pp 37082-37247.

¹⁴ 40 CFR Parts 280 and 281, *Underground Storage Tanks Containing Petroleum, Financial Responsibility Requirements and State Program Approval Objectives*, Final Rule (USEPA, 26 October 1988), pp 4332-4338.

As defined in Subtitle I, a UST system includes both the underground storage tank and the underground piping connected to it. Subtitle I does not apply to the following USTs:

- Farm or residential tanks of up to 1100 gallons capacity used for storing motor fuel for noncommercial purposes
- Tanks storing heating oil for use on the premises where stored
- Septic tanks
- Storage tanks on or above the floor of underground areas such as basements and cellars
- Flow-through process tanks
- Pipeline facilities
- Surface impounding pits, ponds, and lagoons
- Systems for collecting stormwater or wastewater
- Liquid traps or associated gathering lines in use by the oil and natural gas industry.

The Final Rules of September 1988 became effective on 22 December 1988, with phase-in schedules for leak detection devices ranging from December 1989 to December 1993, depending on the system's age.

U.S. Army UST policy, published earlier, is similar to the USEPA's Final Rules. However, there are some differences. The Army USTs (steel or FRP) should be double-walled in structure. Steel USTs must be coated by epoxy or coal tar. These tanks should also be provided with a cathodic protection system or coated with glass fiber-reinforced polyester resin coating. All storage tanks should be monitored by a leak detection system. Tank pipings should have also similar features.¹⁵

Regulated USTs, including those owned and operated by all Federal, State, and local agencies, are required to have leak detection devices, spill and overfill prevention devices, and corrosion protection. Main provisions of the Final Rules require that:

- New UST systems must be designed and constructed to retain their structural integrity for their operating life, in accordance with nationally recognized industry codes
- Nationally recognized installation standards must be followed when placing new UST systems in service
- Owners and operators of new USTs must certify that proper installation procedures were followed, and specify what they were

¹⁵ *Underground POL Systems*, "Underground Storage Tank (UST) Program," Office of the Chief of Engineers (OCE) Memorandum 200 1a (U.S. Army Engineering and Housing Support Center [USAEHSC], October 1987).

- Owners and operators of both new and existing UST systems must follow proper tank-filling practices to prevent spills and overfills
- Owners and operators of new or upgraded UST systems must install devices that prevent overfills, and control or contain spills
- Leak detection procedures must be implemented for the oldest USTs within 1 year, and for the newest systems within 5 years
- Release detection equipment must be added to all pressurized delivery lines within two years
- Periodic tank tightness testing (every 5 years) and monthly inventory control are required for new or upgraded UST systems for 10 years after installation or tank upgrade, and monthly leak detection is required after 10 years
- Either monthly release detection or a combination of annual tank tightness testing and monthly inventory control are required for substandard USTs until they are upgraded
- Existing USTs must be upgraded or closed within 10 years of the effective date of the Final Rules, or within 1 to 5 years, if a leak detection method is not available that can be applied during the required phase-in period
- Secondary containment with interstitial monitoring is required for all new or upgraded USTs storing hazardous substances, unless an alternate release detection method is approved by the regulating agency
- All USTs must be protected against corrosion or made of noncorrodible materials
- Tank owners and operators must report suspected leaks
- Owners and operators of leaking USTs must correct the problem.

Every State is allowed to develop its own UST regulations within the framework of Federal Rules, and several States have already done so.

The Financial Responsibility Final Rule of 26 October 1988 requires petroleum marketers who own or operate USTs to prove that they have at least \$1 million to cover the costs of a leak or spill. UST owners or operators that do not market petroleum must prove that they have at least \$500,000.

The effective date for this rule is 24 January 1989 for any petroleum marketing firm that owns 1000 or more USTs, and any UST owner that reports a tangible net worth of \$20 million or more. The effective date is 26 October 1989 for any petroleum marketing firm that owns 100 to 999 USTs; and 26 April 1990 for any petroleum marketing firm that owns 13 to 99 USTs at more than one site. The deadline is 26 October 1990 for any owner of a UST that falls into one of the following groups. petroleum marketing firms owning 1 to 12 USTs or those with fewer than 100 USTs at one site, all other UST owners with a tangible net worth of less than \$ 20,000; and local governments.

State and Federal governments are exempt from the financial responsibility requirements. However, they are responsible for the costs of any necessary cleanups.

3 LEAK POTENTIAL INDEX FOR UNDERGROUND STORAGE TANKS

Background

Leakage from underground storage tanks occurs through two major mechanisms: corrosion and rupture. External and internal corrosion of a storage tank and its associated piping generally results in the gradual release of its contents into the environment. Loss of material from such releases is barely noticeable, particularly during the early stages when the material loss rate is not substantially larger than the migration and assimilation rates in the soil. On the other hand, structural failures due to settlement, buoyancy, etc., are random events that may or may not occur during the lifetime of a particular tank. The rupture of piping or tank will generally lead to the sudden loss of large quantities of material that would be readily detected under proper inventory control procedures. Corrosion-induced leaks, however, can go undetected for long periods of time.

Leakage may occur due to internal and external corrosion of the steel tank or its attached piping. Losses from piping will generally occur during transfer operations, and the quantity lost will tend to be lower when compared to leakage from the tank itself. Corrosion rates for piping and tank will be similar, except in cases where dissimilar metals are used. For example, if galvanized piping is connected to a steel tank without proper electrical isolation, the piping will be anodic relative to the tank, and will corrode at an accelerated rate. Even if their corrosion rates are similar, pipes may leak earlier than the tank because they are not as thick as the tank. For prioritizing tanks in terms of leak potential, however, this is not of major concern.

Underground storage tanks regulated under Subtitle I of RCRA¹⁶ generally contain petroleum, crude oil, or other distillates, and these are not highly corrosive compared to the hazardous wastes regulated under RCRA Subtitle O. Internal corrosion may be a problem in tanks storing high-sulfur diesel fuels and in cases where a substantial amount of moisture enters the tank through condensation in the vent pipe or from other sources. Internal corrosion begins with imperfections in the coating or coating damage caused by repeated insertions of measuring rods. The bare steel under the damaged coating then becomes anodic relative to other imperfections. Because the probability of external and internal corrosion occurring at the same spot on a tank is very small, internal corrosion is significant only in benign soils and under severe operating conditions.

External corrosion can occur uniformly across the surface of a tank and piping, or by localized intense corrosion known as "pitting." Data about excavated tanks and pipelines indicates that in most cases leakage is caused by pitting of the surface, resulting in pinhole leaks.¹⁷ The development of the leak potential index (LPI) is, therefore, based primarily on the assumption that pitting corrosion is the major mechanism for storage tank failure and material leakage.

¹⁶ Public Law 94-480.

¹⁷ M. Romanoff, *Underground Corrosion*, National Bureau of Standards (NBS) Circular 579 (U.S. Department of Commerce, 1957), J.R. Rossum, "Prediction of Pitting Rates in Ferrous Metals from Soil Parameters," *Journal of Water Works Association*, Vol 60 (1968), pp 305-310, C.T. Bosch, and B.A. Valde, *Consultants Report to the OPA/PACE Special Task Force on Underground Storage Tanks* (1978).

Factors Influencing Underground Storage Tank Corrosion

Corrosion is an electrochemical phenomenon involving oxidation at the anode and reduction reactions at the cathode. Dissolution of the metal occurs at the anode, and, under normal soil pH conditions in aerobic soils, oxygen reduction occurs at the cathode to produce hydroxyl ions. These ions react with the ferrous ions generated by the metal dissolution to produce ferrous hydroxide, or they form precipitates such as calcium carbonate and ferric hydroxide (depending on how well aerated the soil is). In normal soils, the corrosion rate will be a function of measurable parameters such as soil aeration, soil resistivity, and pH. Anodic and cathodic areas are established at different sites on a tank surface due to variations in the soil environment. These variations may arise from a number of factors, including natural soil variations, impurities in the backfill, and differential concentration cells of electrolytes, oxygen, moisture, etc.

In the absence of oxygen, corrosion may be produced biologically. Anaerobic corrosion is caused by a group of bacteria that use hydrogen to reduce sulfate to sulfide. For growth they require anaerobic conditions and a source of hydrogen, sulfate, organic materials, and minerals. These conditions are present in soils that flood frequently and have a high organic matter content. The precise mechanism by which anaerobic corrosion occurs is not well understood. It is generally thought that dissolution of iron may occur through two mechanisms:

- A reaction of iron with sulfide that produces iron sulfide precipitate. In this case, further corrosion is inhibited by the layer of black iron sulfide precipitate.
- As a result of the highly corrosive extracellular metabolite contacting the iron surface.¹⁸ If oxygen is available locally, oxygen concentration cells may develop between the aerobic and anaerobic zones, and the hydrogen sulfide may be oxidized to highly corrosive sulfuric acid.

Development of Leak Potential Index Equation

It is evident from the foregoing discussion that numerous factors are involved in UST corrosion, and any assessment methodology developed must consider site-specific data. Some soil parameters of importance are: soil resistivity, pH, soil permeability or aeration, organic matter content, sulfate content, water table, flooding frequency, soil variations, and shrinkage potential. In aerobic soils, the first three parameters determine corrosion rates once anodic and cathodic areas are established. The latter factors are important in establishing anodic and cathodic areas, and the start of corrosion.

Evaluation of UST leakage potential can be based on statistical analysis of data for excavated tanks, or from a mechanistic standpoint. Accurate data is quite limited for soil properties at a tank site and the age at which a tank leaked. Therefore, equations based on statistical analysis are of limited validity. A mechanistic approach will be more reliable since it is not only based on fundamental principles, but also can be related to extensive experimental data developed by the National Bureau of Standards.

¹⁸ W.P. Iverson, *An Overview of the Anaerobic Corrosion of Underground Metallic Structures, Evidence of a New Mechanism, in Underground Corrosion*, Technical Publication 741 (American Society for Testing and Materials [ASTM], 1981).

Analysis Based on UST Leak Data

Data on underground storage tanks was developed over a 6-month period in 1977 by the Petroleum Association for Conservation of the Canadian Environment (PACE).¹⁹ A total of 506 tanks were removed across Canada and examined for localized and uniform corrosion. All available soil samples were analyzed for a number of parameters, such as resistivity, pH, moisture, and bacterial content. The number of tanks that had one or more perforations was determined to be 124, and of these only 108 tanks had corresponding soil data. Numerical values were assigned to each of the soil parameters, and differential soil characteristics, or variations in resistivity and pH at the site (Table 1). Soil "aggressiveness" values (SAV)—the quantification of a soil's corrosive properties—were computed for each location based on the above for leaking and nonleaking tanks. Values of 10 to 12 indicate aggressive soils, and values greater than 12 are characteristic of very aggressive soils.

The SAV values are shown in Figures 4 and 5 for leaking and nonleaking tanks as a function of age. There is considerable scatter in the data in both figures. A number of tanks with low SAVs and low to medium age ratings leak nonetheless. Figure 5 also shows a number of tanks that are not leaking despite high SAVs and medium to high age ratings. After considerable statistical analysis it has been concluded that neither SAV nor SAV multiplied by age are reliable indicators of tank deterioration.²⁰

Bosch and Valde, and Rogers²¹ have used the Canadian data to develop the following equation to calculate the mean age for UST leakage:

$$MA = 5.75 R^{0.05} S^{-0.018} \exp(0.13pH - 0.41M - 0.26Su) \quad [Eq 1]$$

where MA = Age at which 50 percent of the tanks at a given location would have leaked

R = Resistivity in ohm-cm

S = Tank capacity in gallons

M = 1, if soil is saturated; 0, otherwise

Su = 1 if sulfide is present; 0, otherwise.

This model assumes that the age to leak is a normal random variable, and predicts the mean age to leak with a standard deviation of 2.5 years. Approximately 50 percent of the tanks at a site would be expected to have leaked before the mean age, and 50 percent would be expected to leak sometime after the mean age. For a tank of known age, it is possible to use this equation to determine the probability that the tank is leaking.

¹⁹ *Underground Tank Systems Review of the State of the Art and Guidelines*, Report No. 82-3 (Petroleum Association for Conservation of the Canadian Environment [PACE], Ottawa, Canada, 1983).

²⁰ Pope-Reid Associates, Inc., *Hazardous Waste Tank Failure Model. Description of Methodology* (USEPA, 1986).

²¹ W.F. Rogers, "Rogers Finds Leaks By Using Statistics," *Petroleum Marketer* (November-December 1982).

Table 1
Computation of Soil Aggressiveness Values

I BASIC CHARACTERISTICS		POINTS
• Soil Resistivity (in ohms)	< 300	12
	300 - 1,000	10
	1,001 - 2,000	8
	2,001 - 5,000	6
	5,001 - 10,000	3
	10,001 - 25,000	1
	> 25,000	0
	< 3.0	8
	3.0 - 4.9	6
	5.0 - 6.4	4
• Soil pH	6.5 - 7.4	2
	7.5 - 9.0	1
	> 9.0	0
	Saturated	3
	Damp	2
• Soil Moisture	Dry	0
II DIFFERENTIAL CHARACTERISTICS		
• Resistivity (ratio of extremes)	>1:10	3
	>1: 5	2
	>1: 3	1
	<1: 3	0
	3	2
• Soil pH (Difference in pH Value)	1.5 - 3.0	1
	0.0 - 1.5	0
III SULFIDE CONTENT		
	Positive	4
	Negative	0

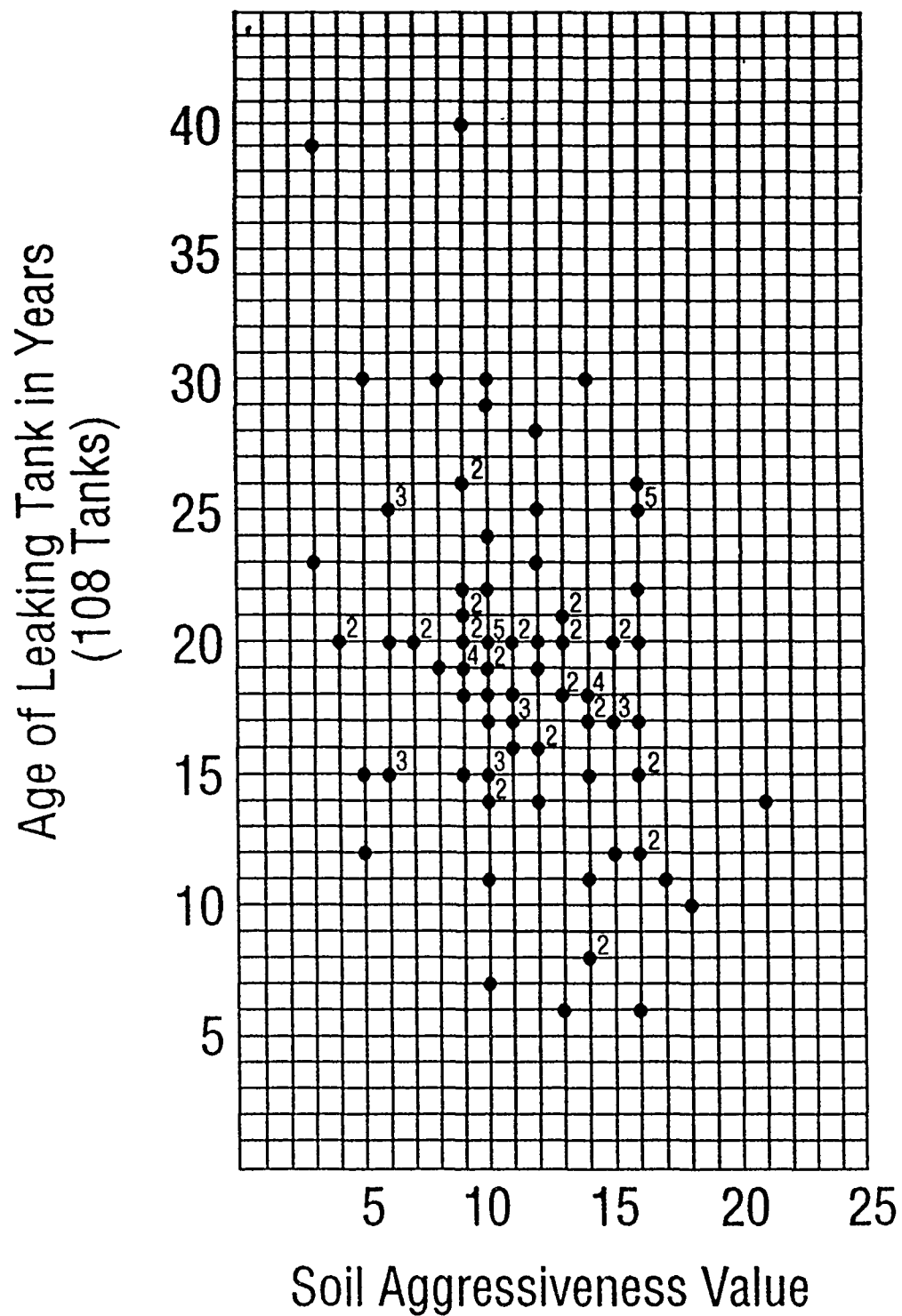


Figure 4. Leaking tank chart indicating the relationship between soil aggressiveness values and age.

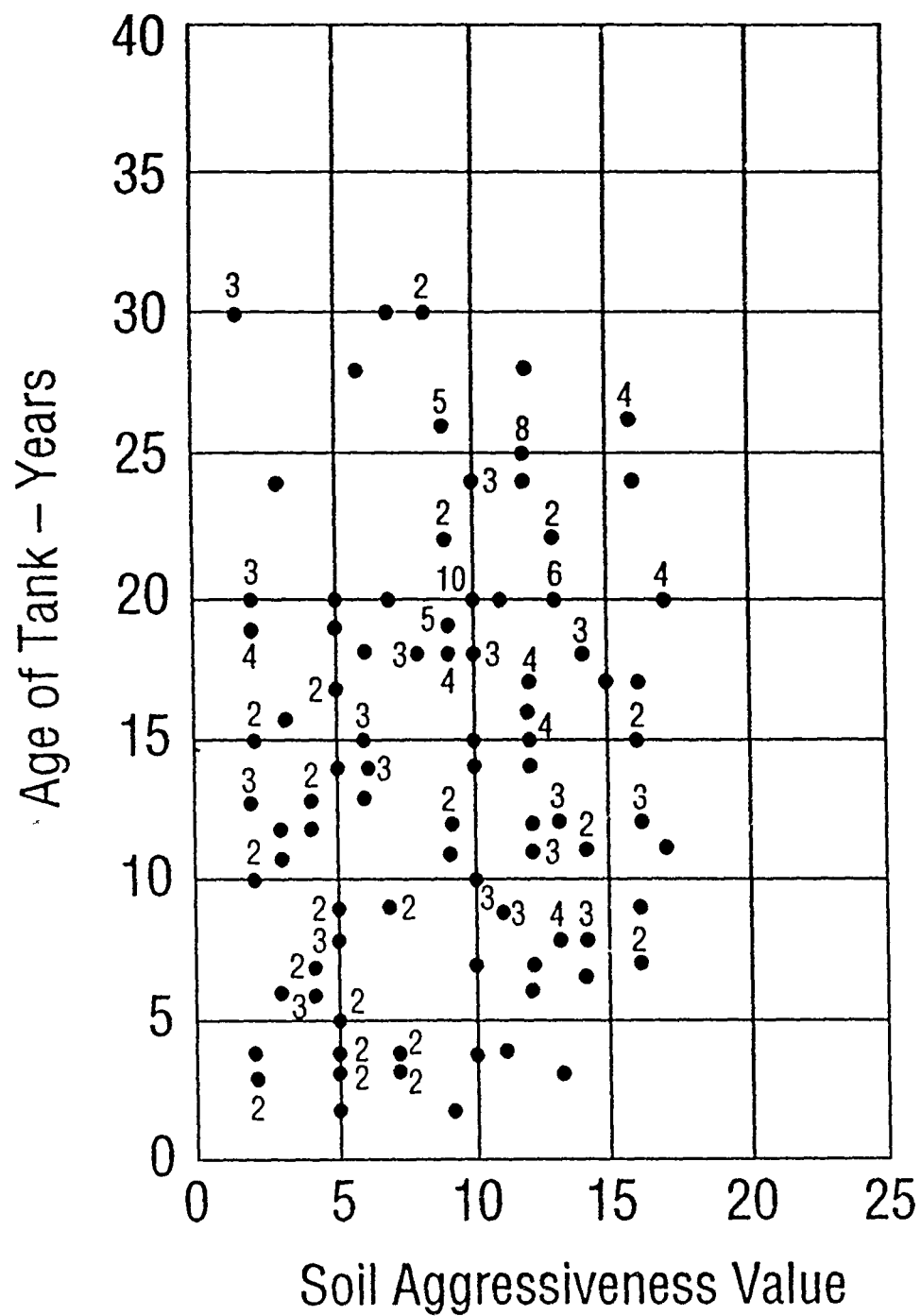


Figure 5. Nonleaking tank chart indicating the relationship between soil aggressiveness values and age.

Both approaches noted above have some practical limitations. First, they are based on a very small number of gasoline tanks (108) that range in size from 1000 to 5000 gallons. The sample under consideration in this report ranges in size from 500 gallons to more than 100,000 gallons. Second, the age at which a tank was excavated and found leaking may not indicate when the tank actually started leaking.

Analysis Based on Corrosion Mechanism

It is known from electrochemical principles that corrosion occurs through the loss of metal ions at anodic areas. In laboratory systems, the rate at which metal loss occurs can be estimated from Faraday's law. Application of this theory to underground corrosion is complicated because of the variables that singly, or in combination, affect the electrochemical reaction. The nature of cathodic reactions, precipitate formation, diffusion of a tank's contents, diffusion of oxygen to the cathodic surface, etc., will all affect the progress of the reaction.

The National Bureau of Standards²² has determined from extensive experimental studies that the depth of a pit due to localized corrosion can be expressed by the equation

$$p = kt^n \quad [\text{Eq 2}]$$

where p is the pit depth, t is the time of exposure, and k and n are constants. This equation has been found valid for several types of ferrous materials. Rossum subsequently derived Equation 2 from electrochemical principles and postulated mechanisms for reactions between metal and soil under differing soil aeration conditions. The exponent was shown to have values of 0.17, 0.33, and 0.5 for soils of good aeration, fair aeration, and poor aeration, respectively. These values for n agree well with the empirical values reported by the National Bureau of Standards. The constant k is a function of the number of systems parameters such as soil resistivity, corrosion potential, and aeration.

The soil resistivity at any given site is not uniform, and varies log-normally.²³ The maximum pit depth on a metal surface, therefore, will also increase log-normally with the increasing area under consideration.²⁴ The time and area effects are combined²⁵ to produce the following equation for the number of leaks, L , that can be expected after exposure for t years:

$$L = A * \{(K_n K_a / \delta) * (t(10 - \text{pH}) / \sigma)^n\}^{1/a} \quad [\text{Eq 3}]$$

where

- A = exterior surface area of the pipe, in square feet;
- K_n and n = constants based on permeability of the soil and soil aeration;
- K_a and a = constants based on permeability of the metal (relative pit depth, pit depth);
- δ = shell thickness of the pipe, in mils;
- t = time of exposure of the pipe, in years;

²² M. Romanoff.

²³ B. Husock, *A Statistical Probability Method for Soil Resistivity Determination in Underground Storage Corrosion*, ASTM Technical Publication 741 (ASTM, 1981), G.N. Scott, "Distribution of Soil Conductivity and its Relation to Underground Corrosion," *Journal of the American Water Works Association* (March 1960), W.J. Schwerdtfeger, "Soil Resistivity as Related to Underground Corrosion and Cathodic Protection," *Journal of Research of the National Bureau of Standards*, Vol 69C (1960).

²⁴ W.J. Schwerdtfeger; M. Romanoff.

²⁵ J.R. Rossum.

pH = acidity/alkalinity of the soil;
 σ = soil resistivity, in ohm-cm.

Equation 3 was developed by combining an empirical pit depth - area relationship and a theoretical pit - time equation. It applies to soils ranging from pH5 to pH9 and aeration conditions ranging from poor to good. When known values of soil resistivity and pH are used, the calculated pit depths correlate well to experimental pit depths calculated in laboratory studies. Rossum used Equation 3 to calculate the number of leaks in a number of cast iron and steel pipes buried in soil at different locations for several years. The pipes were partially corroded, and some of them had several holes. His predictions reasonably matched the number of leaks observed.

Corrosion rates in Equation 3 do not take into account the effects of expansive soils, flooding frequency, high water table (and accompanying anaerobic conditions), and organic matter content. These factors, on which numerical rankings and values are available in the U.S. Soil Conservation Service (SCS) soils database, have been assigned weights similar to those employed by PACE and the Cast Iron Pipe Research Association (CIPRA).²⁶

Expansive soils can have two different effects on USTs. They can pull the coating off the tank surface when shrinking, and deform the coating by compression when expanding. Areas where the coating is damaged will become anodic and will become susceptible to corrosion. These soils can also crack during shrinkage to provide effective channels for localized oxygenation. Under these conditions, differential oxygen cells may be formed.

Flooding frequency can also influence the extent of corrosion. If the tank is partially flooded, differential cells can be established between the wet and dry areas. The wet areas may be anaerobic and the dry areas aerobic. Both sulfur-reducing and sulfur-oxidizing bacteria may thrive under conditions of alternate flooding and drying, creating a highly corrosive environment. If the water table is consistently high, as in poorly drained soils, then conditions are favorable for anaerobic bacterial corrosion—particularly when the organic matter content is high. On the other hand, in arid regions of the West corrosion potential may not be high even where the soil is poorly drained, because water tables are low. Tanks located in peat or muck soils, however, are susceptible to severe corrosion.

If the soils within an area have several different map unit components (i.e., several different soil types), then long-line corrosion can result. The larger the number of components, the greater the potential for corrosion from this source. The map unit component number obtained from SCS soils data base is used to account for this effect.

Leak Potential Index Equation

The leak potential index, LPI, is the maximum value derived by evaluating all soil map units in the soil survey area where the tanks are located, and is calculated by the equation

$$LPI = \log[C_i * A * \{(K_p K_s / \delta) * (t(10 - pH) / \sigma)^n\}^{1/4}] \quad [\text{Eq 4}]$$

²⁶ *Cast Iron Pipe Research Association Handbook* (Cast Iron Pipe Research Association [CIPRA], Oak Brook, IL, 1978).

The product of the terms in square brackets, "[]," can range from 0 to a very large number. Therefore, a logarithm of the product provides an index on a more manageable linear scale.

C_i in Equation 4 is determined as a product of the four factors: shrink-swell potential of the soil, number of map unit components, flooding frequency and water table, and organic matter content. The values assigned for shrink-swell potential of 1.33, 1.17, and 1.0 correspond to high, medium, and low categories, respectively. The number of soil components in a map unit are indicated by the map unit components factor. This factor has the values of 1.0, 1.17, 1.33, and 1.5 for one, two, three, and four or more components, respectively. Flooding frequency is categorized in the SCS database as common, frequent, occasional, rare and none. The corresponding values used for the factor are 1.33, 1.2, 1.1, 1.05, and 1.0 respectively. If the water table is higher than 6 ft, the water table factor has a value of 1.0. For a water table depth less than 6 ft, and organic content less than 6 percent, a value of 1.5 was assigned to the factor. This factor was assigned a value of 2 for a water table less than 3 ft and organic matter content between 2 and 6 percent.

The probability that a tank is located in a map unit for which the relevant soil parameters are available is determined by the percentage of land in that map unit within the survey area. The acreage of land with specific characteristics in each map unit is obtained from the SCS soils database, and the ratio of this value to the total acreage in the survey area is the variable PCT in Equation 4.

The surface area of a tank (A , in square feet) can be estimated from the reported capacity:

$$A = 1.5 * C^{2/3} \quad [\text{Eq 5}]$$

where C is the tank capacity in gallons. This equation was obtained by assuming a tank length to diameter ratio of 3:1.²⁷

The shell thickness does not increase linearly with tank capacity. Shell thickness values for distinct tank capacity intervals were determined for commercially available tanks²⁸ as shown in Table 2. If tank capacity was not reported on the UST notification form (USEPA 7530-1), a median capacity value of 7600 gallons was assigned, based on the reported capacity data for tanks in the Army UST database. The thickness of a tank wall (in mils, or 0.0254 mm) was based on tank capacity, as shown in Table 2.

Soil resistivity (σ) and pH values were obtained from the salinity (or 1000/resistivity) and pH data available in the SCS database. Salinity values in the database are inversely proportional to the soil resistivity. For cases where salinity values are not available in the SCS database, the soil corrosivity description in the database was used to assign numerical values for salinity. Numerical values of 8, 4, and 2 were assigned for salinity to represent high, medium, and low degrees of corrosivity, respectively.

K_a and a are constants that represent tank permeability and, by evaluating pit depths, were determined to be 1.06 and 0.16 for steel tanks. K_n and n are constants that reflect soil permeability. Their values were obtained from the SCS database, and are shown in Table 3.

²⁷ R. Holzhauer, "Underground Liquid Fuel Storage Tanks," *Plant Engineering* (April 1980).

²⁸ R. Holzhauer.

The age of the tank is required to be reported in the USEPA UST notification form. In several cases, however, the age of the tank was not reported, possibly due to lack of documentation. For cases in which the age of the tank was not reported or was unknown, the age was assumed to be 50 years.

Table 2
UST Shell Thickness as a Function of Capacity*

Tank Capacity (gallons)^a	Shell Thickness (mils)^b
≤ 285	78
286 to 550	109
551 to 1,500	141
1,501 to 4,000	188
4,001 to 11,600	250
11,601 to 20,000	313
20,001 to 30,000	375
30,001 to 100,000	500
≥ 100,000	625

^a 1 gallon = 3.785 liters

^b 1 mil = 0.0254 mm

* Source: R. Holzhauer

Table 3
Soil Aeration Constants*

Soil Permeability (in./hour)^a	n	K_n
≤ 0.6	0.50	355
0.6 to 2.0	0.35	222
≥ 2.0	0.17	170

^a 1 in./hour = 0.423 mm/hour = 0.0071 mm/second

* Source = J. R. Rossum.

4 CHARACTERISTIC PROFILE OF ARMY'S UNDERGROUND STORAGE TANKS

UST Database

Because of the large quantity of information about USTs obtained from installations, Army headquarters tasked USACERL with developing a system to better monitor and manage these tanks. Figure 6 shows the number of USTs in each of the following major installation categories: AMC, FORSCOM, TRADOC, NGB, and other.* The result was the microcomputer-based database developed in dBase III Plus.²⁹

The UST database system contains the following information for all 15,284 tanks: MACOM, installation name, specific address (where each tank is buried), and number of tanks at each location. Other information about each tank in the database includes: current status, year installed, construction material, capacity, corrosion protection, type of piping, contents, and other miscellaneous information.

The UST database system is menu-driven and easy to use. With this system, the user can perform the following functions:

- **Retrieve specific UST information** — allows users to retrieve information about each tank buried at any Army installation
- **Calculate a leak potential index (LPI)** — allows users to calculate the LPI for any tank in the database. (The LPI is a quantitative indicator of the potential for any tank to leak)
- **Perform file maintenance** — allows users to back up database files, organize them into smaller subsets of data, etc.
- **Update existing UST information** — allows users to update information for USTs already listed in the system
- **Add new UST information** — allows users to add information about new tanks to the database
- **Delete UST information** — allows users to delete the appropriate records from the database as USTs are removed from use
- **Create UST reports** — allows users to create customized reports.

The rest of this chapter is a profile of the Army's USTs based on the database. The status of the Army's tanks will be discussed from an overview perspective and will not pertain to any specific installation.

* AMC is U.S. Army Materiel Command, FORSCOM is U.S. Army Forces Command, TRADOC is U.S. Army Training and Doctrine Command; NGB is U.S. Army National Guard Bureau.

²⁹ B.A. Donahue, T.J. Hootor, and K. Piskin.

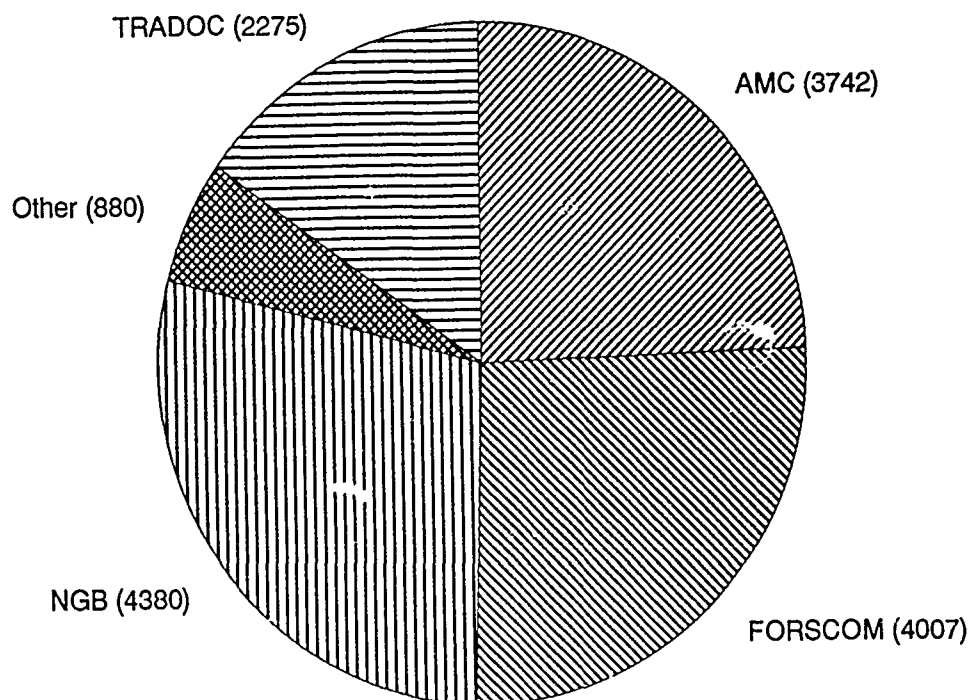


Figure 6. Distribution of the 15,284 USTs among MACOMs.

Construction Material

Steel is the most common UST construction material, followed by FRP and concrete. Figure 7 shows the distribution of tank construction materials among Army installations. Of all of the Army's current tanks, 73.5 percent (11,234) are made of steel, 9.1 percent (1390) of FRP, 1.3 percent (198) of concrete, and 0.14 percent (20) of miscellaneous materials. The construction material was reported as unknown for 16 percent (2445) of the tanks.

Only 33 percent (4984) of steel tanks have some form of external corrosion protection (mainly painted, cathodically protected). The rest are either unprotected or status unknown.

Capacity

If an underground storage tank has a capacity of 110 gallons or less, it is exempt from regulatory reporting and management requirements. Despite the exemption, installations were directed by Army headquarters to report on all their tanks. Figure 8 shows the distribution of tanks at Army installations according to capacity in gallons. As indicated in the figure, very few of the reported tanks fall under the size exclusion.

Age

The age of a tank was determined from the time it was installed up to 1990. The age distribution of the tanks among the different Army installations is shown in Figure 9. For about 14 percent (1785) of all Army tanks, the age was reported as unknown, mainly because these recordkeeping requirements were not in place at the time of installation. Thirty percent (3706) of the tanks were reported to be over 25 years old, 30 percent (3718) were between the ages of 10 and 30 years, and 26 percent (3315) were under 10 years old.

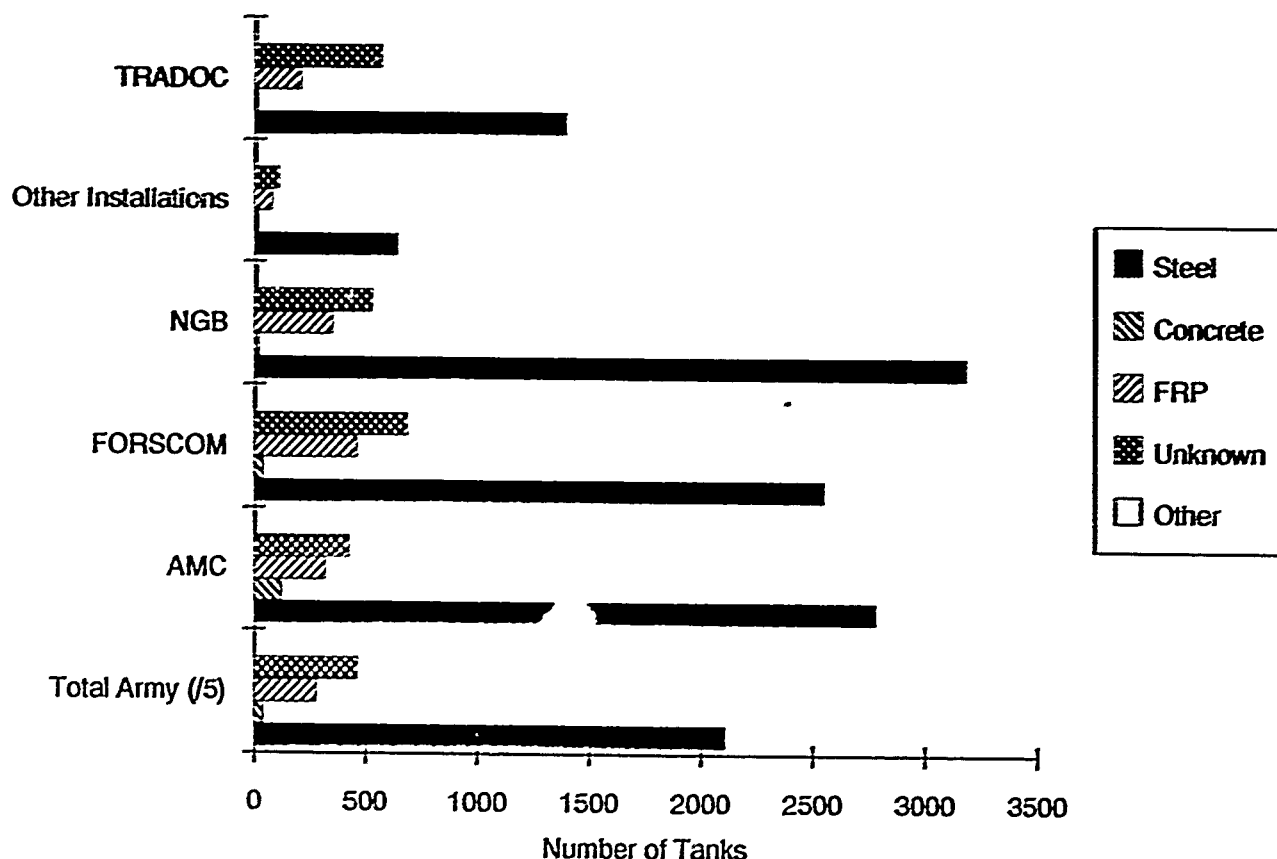


Figure 7. Distribution of USTs according to construction material among MACOMs. (Note: The total number of tanks in the Army for any category of material can be calculated by multiplying the figure at the bar width by 5.)

Tank Contents

On the USEPA forms, Army installations were required to report the contents of each tank. The categories provided were: gasoline, diesel, kerosene, used oil, and other. If the tank contents were specified as other, a text field is provided to allow for a specific description of the tanks' contents to handle items such as heating oil which are of interest, but did not have a category assigned to them. If the contents were not reported, they were assumed to be unknown. Figure 10 shows the distribution of contents by MACOMs. Of particular interest is the number of reported tanks (4341) that contain heating oil. Presently, the Army does not allow the EPA exclusion on heating oil tanks in its policy. A breakdown of those tanks containing heating oils, by capacity, is presented in Figure 11.

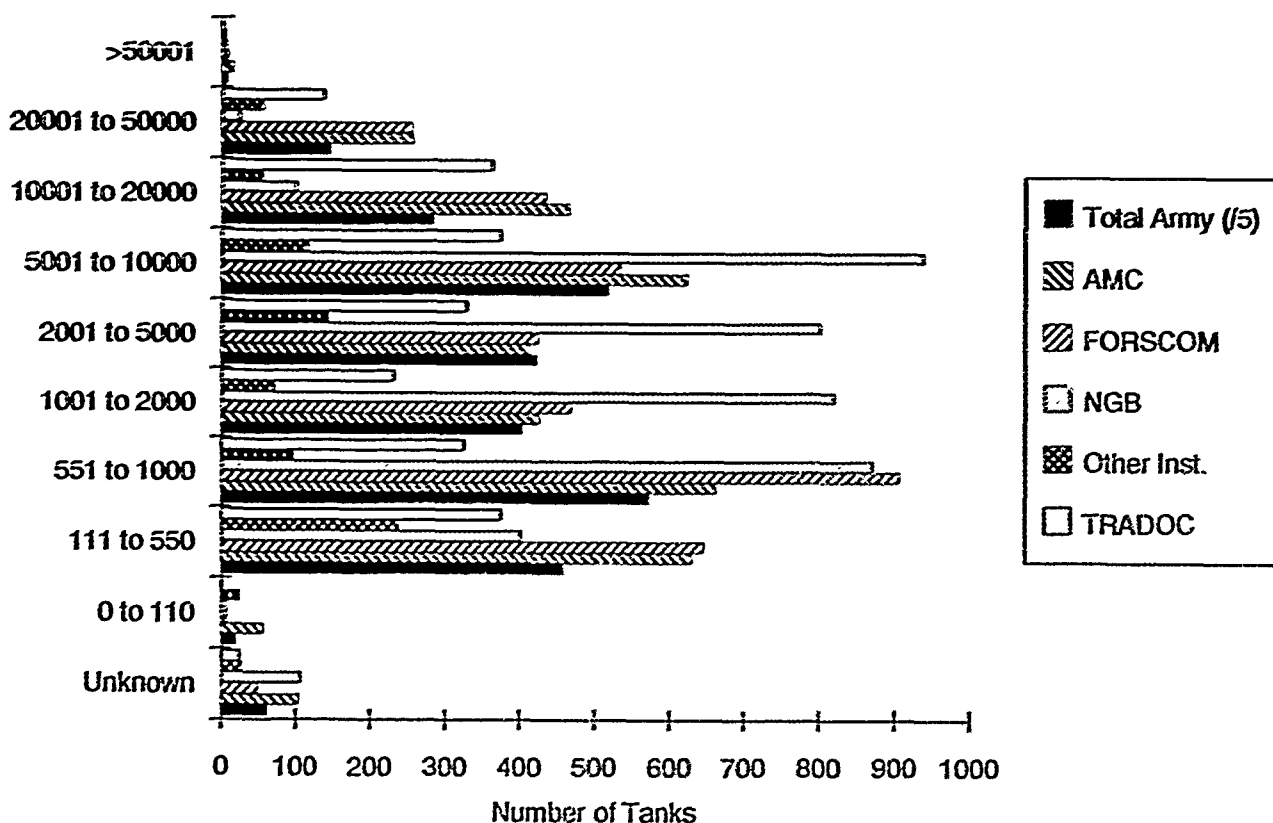


Figure 8. Distribution of USTs according to capacity (in gallons) among MACOMs. (Note. The total number of tanks in the Army for any category of capacity can be calculated by multiplying the figure at the bar width by 5.)

Leak Potential Index (LPI)

The information available in the UST database was used to compute a leakage potential for all the Army's USTs. In addition to the tank information, soil information was necessary to obtain LPI values. The soil data was obtained from the SCS database, maintained at Iowa State University. It contains information on each soil type in each county and State in the United States.

Equation 4 is evaluated for each tank for all soil types in a county and a weighted average is computed based on the percentage of each soil type in that country. The computed values of the LPI are then categorized as follows: 0 to 2 (low), 2 to 4 (medium), and greater than 4 (high). The distribution of LPIs computed for all Army USTs is shown in Figure 12.

The results of the LPI calculations for the Army's USTs are to be field-tested for tanks buried at various installations. Efforts are also being made to update the tank and soil information in the database so the LPIs for all tanks can be calculated more accurately and completely. Also, a relationship similar to Equation 4 has been developed for underground pipes, and has been successfully field-tested at many Army installations.³⁰

The sensitivity of the LPI equation to its parameters is of concern due to the large uncertainties inherent in the approach used to determine soil information. Specifically, the soil information is taken from the SCS soils database, which has the country at its lowest discernable geographic region.

Since the LPI equation involves several noncontinuous parameters (tank size, wall thickness, and soil permeability) and several that have strongly nonlinear effects (salinity and pH), the behavior of the LPI equation is presented in terms of variations about a typical LPI. This LPI is defined for a tank of median age and capacity with average soil parameters (defined as the mean for all tanks in the UST database for which soil exists). Specific numerical values are given below.

Tank Age	25 years
Tank Capacity	2000 gallons
Kn	222
n	0.33
pH	6.2
Salinity	6.45
Cf	1.37
LPI	2.65

³⁰ A. Kumar, M. Bergerhouse, and M. Blyth, "Implementation of a Pipe Corrosion Management System," *Corrosion* 87, Paper Number 312 (1987).

Response of the LPI about this typical value of 2.65 for specific variations in the independent parameters are give below.

<u>Parameter</u>	<u>Value</u>	<u>LPI Variation</u>
Tank Age (years)	10	-0.82
	40	0.42
Tank Capacity	500	1.08
	5000	-0.51
Permeability	high	-0.95
	low	1.49
pH	5.05	0.24
	7.35	-0.32
Salinity	2.43	-0.87
	10.47	0.43
Cf	1.00	-0.14
	1.74	0.10

where the tank ages of 10 and 40 years correspond to 20 and 80 percent ranking by age, the tank capacities of 500 and 5000 correspond to 19 and 70 percent ranking by capacity, the permeability values represent variations in the Kn and n coefficients from their minimum to maximum values, and the other soil parameter variations are values one standard deviation about their respective means.

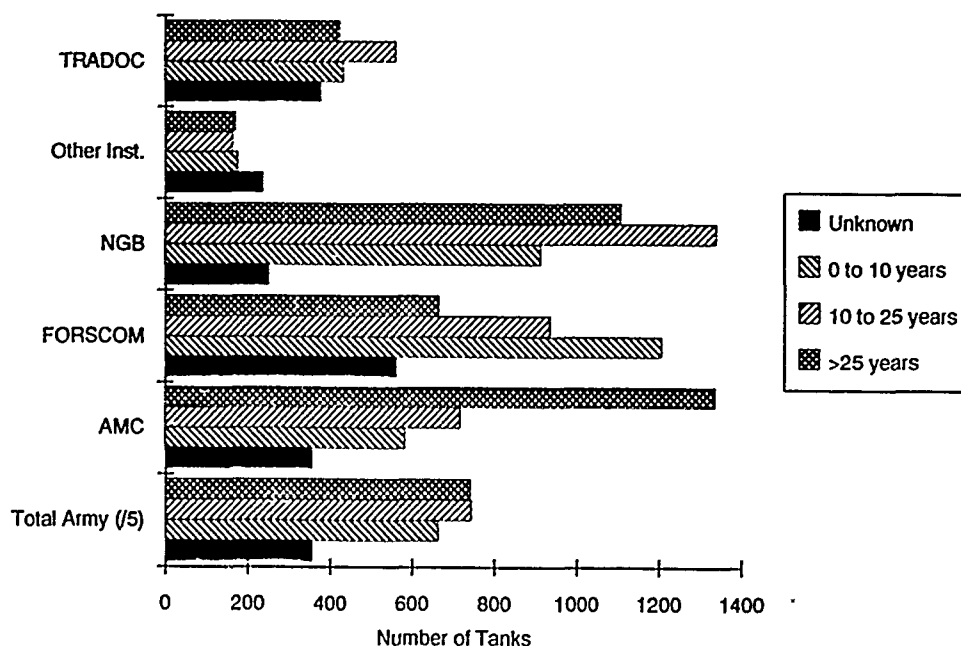


Figure 9. Distribution of USTs according to age (in years) among MACOMs. (Note: The total number of tanks in the Army for any category of age can be calculated by multiplying the figure at the bar width by 5.)

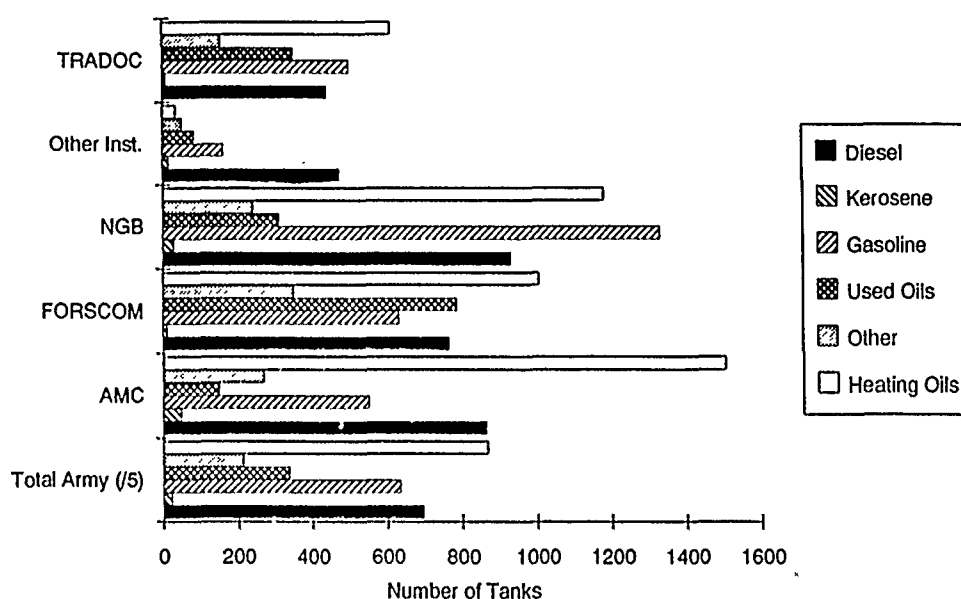


Figure 10. Distribution of USTs according to content by MACOM. (Note: The total number of tanks in the Army for any category of content can be calculated by multiplying the figure at the bar width by 5.)

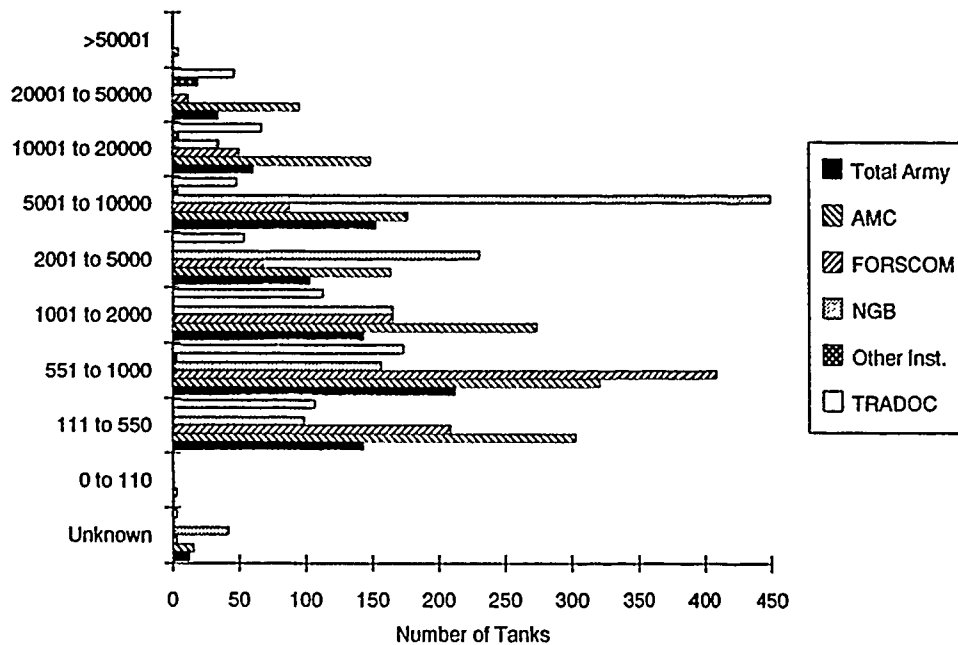


Figure 11. Distribution of USTs by capacity (in gallons) for all USTs containing heating oil. (Note: The total number of USTs owned or operated by the Army in any category of tank capacity [black bars] can be calculated by multiplying the figure at the bar width by 5.)

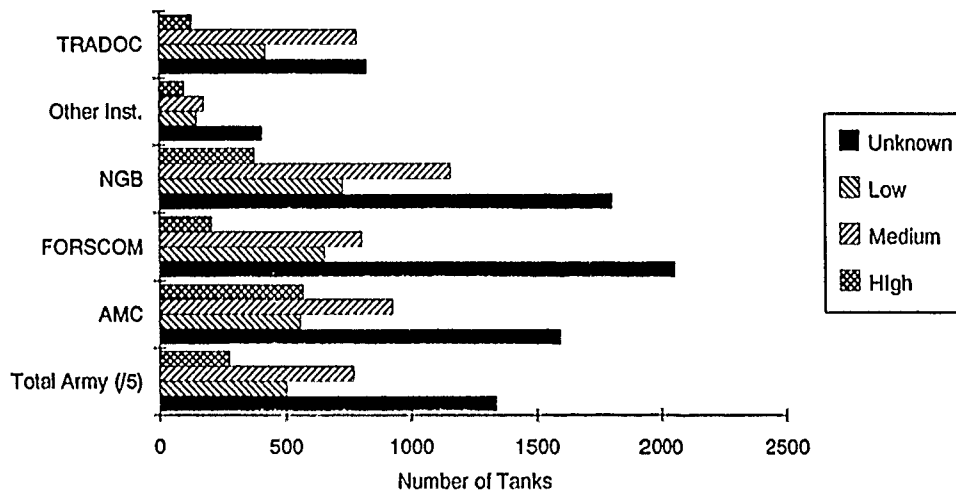


Figure 12. Distribution of USTs according to LPI among MACOMs. (Note: The total number of tanks in the Army for any category of LPI can be calculated by multiplying the figure at the bar width by 5.)

5 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

A Leak Potential Index (LPI) has been devised to indicate the likelihood of individual underground storage tank leakage. The LPI, which is based on the UST database and soil information, enables Army managers to evaluate their tanks and categorize them according to their leakage potential. This information indicates which tanks should be monitored more closely, which should be tested, and which should be considered for replacement. The results of this analysis will help guide decisions about the management and maintenance of the Army's USTs.

Many of the Army's USTs are made of steel, hold more than 10,000 gallons, are more than 35 years old, may contain hazardous substances, and have a high potential for leakage:

- Seventy-three percent of the Army USTs are made of steel. NGB has the most steel tanks, most of which range in capacity from 1101 to 10,000 gallons
- AMC has the largest number of tanks greater than 10,000 gallons
- Thirty percent of the Army's USTs have been in the ground for more than 25 years. FORSCOM has the most tanks of unknown age. NGB has the most tanks between 10 and 25 years of age.

Heating oil is generally the most common substance stored in the Army's USTs, followed by diesel fuel, gasoline, used oil, and kerosene. Mixed substances and others are also stored in a number of tanks, with FORSCOM having the most in this category.

The LPI could not be computed for 46 percent of the USTs because of insufficient tank and soil data. FORSCOM had the most tanks for which no LPI could be computed, followed by NGB, AMC, and TRADOC installations (in that order). Only 9 percent of the tanks have a very high LPI. Twenty-seven percent of the tanks can be categorized as medium and 17 percent low in terms of LPI.

Recommendations

It is recommended that the information in this report (i.e., construction material, capacity, age, content, and LPI of USTs) be used by Army decisionmakers involved in compliance with environmental regulations. Missing data and unknown LPIs for 46 percent of the Army's USTs must prompt managers to take action. Efforts are being made to collect the missing information so the database can be updated, after which the LPIs for all tanks will be evaluated again.

It is recommended that the techniques of developing a database and the use of a relationship to determine leak potential be adapted and used by all owners and managers of USTs. Policy makers can use information from the database to plan effective management and pollution control policies. Federal and State agencies can use the database concept and LPI to identify problems and plan strategies to prevent land and groundwater pollution.

It is recommended that the tanks predicted most likely to leak be tested immediately. If leaking tanks are found they must be excavated, and proper pollution treatment and control measures must be implemented.

It is recommended that further site-specific studies be conducted and additional field data be collected to develop monitoring frequencies, repair and replacement strategies, and to field test LPI predictions.

METRIC CONVERSION TABLE

1 ft	=	0.3 m
1 sq ft	=	0.0929m ²
1 in.	=	25.4 mm
1 in./hr	=	0.0071 mm/sec
1 mil	=	0.0254 mm
1 gal	=	3.785 liters

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ABBREVIATIONS

AMC	U.S. Army Materiel Command
ASTM	American Society for Testing and Materials
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CIPRA	Cast Iron Pipe Research Association
CONUS	Continental United States
FORSCOM	U.S. Army Forces Command
FRP	Fiberglass-Reinforced Plastic
HSWA	Hazardous and Solid Waste Amendments
LPI	Leak Potential Index
MACOM	Major Army Command
NBS	National Bureau of Standards
NGB	U.S. Army National Guard Bureau
OUST	Office of Underground Storage Tanks
PACE	Petroleum Association for Conservation of the Canadian Environment
RCRA	Resource Conservation and Recovery Act
SAV	Soil Aggressiveness Value
SCS	U.S. Soil Conservation Service
TRADOC	U.S. Army Training and Doctrine Command
USACERL	U.S. Army Construction Engineering Research Laboratory
USEPA	U.S. Environmental Protection Agency
UST	Underground Storage Tank

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325
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